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ANALYTICAL MODEL OF AN ANNULAR MOMENTUM CONTROL DEVICE (AMCD) LABORATORY TEST MODEL MAGNETIC BEARING ACTUATOR

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ANALYTICAL MODEL OF AN ANNULAR MOMENTUM CONTROL DEVICE (AMCD) LABORATORY TEST MODEL MAGNETIC BEARING ACTUATOR

by

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SUMMARY

An analytical model of an Annular Momentum Control Device (AMCD) laboratory test model magnetic bearing actuator with permanent magnet flux-biasing is presented. An AMCD consists of a spinning annular rim which is suspended by noncontacting magnetic bearings and driven by a noncontacting linear electromagnetic spin motor. The actuator is treated as a lumped-parameter electromechanical system in the development of the model.

INTRODUCTION

The basic concept of the Annular Momentum Control Device (AMCD) is that of a rotating annular rim suspended by noncontacting magnetic bearings and powered by a noncontacting linear electromagnetic motor. A detailed discussion of the rationale for the AMCD configuration and its potential applications are presented in reference 1. Earth-based energy storage applications of the concept are discussed in references 2 through 4.

In order to investigate any potential problems in implementing the AMCD concept, a laboratory test model AMCD was designed and fabricated under contract. The laboratory model has been delivered and preliminary tests have been performed. Reference 5 presents a detailed description of the laboratory model and reference 6 presents results of static and low-speed dynamic tests which include spin motor torque characteristics and spin motor and magnetic bearing drag losses. Reference 6 also briefly discusses permanent magnet flux-biasing. Previous analyses of the laboratory model AMCD (including refs. 5 and 6) have utilized a linear model of the magnetic bearing actuator. One limitation of the linear model is that it is accurate only in a small region about a given operating point in the bearing gap. The purpose of this report is to develop a nonlinear analytical model of the AMCD laboratory model magnetic bearing actuators which can be used in computer simulations to investigate the effects of large rim motions in the bearing gaps.

SYMBOLS

A	cross sectional area of magnetic bearing element core
B	magnetic flux density
B_m	magnetic flux density in permanent magnet element
B_o	residual magnetic flux density in permanent magnet element
C	contour
E	electric field intensity
E'	electric field intensity measured with respect to a contour that may be moving
F	net force produced by magnetic bearing actuator
F_L	force produced by lower magnetic bearing element
F_T	total force acting on suspended mass
F_U	force produced by upper magnet bearing element
f_e	force of electric origin
g	magnetic bearing element gap
g_L	lower magnetic bearing element gap
g_U	upper magnetic bearing element gap
H	magnetic field intensity
H_m	magnetic field intensity in permanent magnet element
I_o	defined by equation (29)
i	current
i'	defined by equation (35)
J_f	current density

K_A	position gain
K_B	electromagnet gain
K_m	equivalent permanent magnet stiffness
K_R	rate gain
K_1	defined by equation (39)
K_2	defined by equation (39)
ℓ	length of permanent magnet element
M	magnetization density
m	mass
N	number of turns in electromagnet winding
n	normal vector
s	laplace variable
v	voltage
W	weight
W_m	total energy stored in magnetic field
W'_m	coenergy
X_m	magnetic susceptibility
x	displacement
x_o	bearing gap with rim centered
$\hat{x}$	position sensor output
$\bar{x}_o$	defined by equation (41)
λ	flux linkage
μ	permeability

μ_m	permeability of permanent magnet material
μ_o	permeability of free space
ϕ	magnetic flux
$\triangleq$	equal by definition

SINGLE ELEMENT MODEL

In this section the force equations of a single magnetic bearing element are developed. The element is treated as a lumped-parameter electromechanical system and the magnetic field equations used in the development are presented in Appendix A. For a detailed treatment of lumped-parameter electromechanical systems see reference 7.

Electromechanical Coupling

Electromechanical coupling is modeled as a lossless magnetic field system which couples an electrical terminal pair with variables i and λ and a mechanical terminal pair composed of a node x acted on by an electrical force f_e. Flux linkage, λ, is discussed in Appendix B. All mechanical energy storage and electrically dissipative elements are assumed to be connected to the terminals externally leaving only elements that store energy in the magnetic field. Because of this the assumption is made that the force of electric origin, f_e, has a single value for a given i and x. That is,

$$f_e = f_e\,(i,x) \tag{1}$$

Energy Considerations

Let W_m be the total energy stored in the magnetic field. The conservation of power can be written as

$$iv = f_e \frac{dx}{dt} \tag{2}$$

where iv is the time rate of change of energy (power) going into the electrical terminals and $f_e \frac{dx}{dt}$ is the resulting time rate of change of energy going into the mechanical terminals. Or, in terms of energy, equation (2) can be written as

$$\frac{dW_m}{dt} = i\,\frac{d\lambda}{dt} - f_e \frac{dx}{dt} \tag{3}$$

where the relationship of equation (B5) has been used for v. Eliminating dt results in the conservation of energy

$$dW_m = i\, d\lambda - f_e\, dx \tag{4}$$

Next, choose the independent variables λ and x which determine i and f_e through the terminal relations. The change in W_m due to changes in λ and x can then be found by integration of the above equation. This will be a line integration in two dimensional variable space and since the system is conservative, the stored energy is a function of its state and is independent of the path taken to reach that state. Choosing path 1, 2, 3 in figure 1 results in

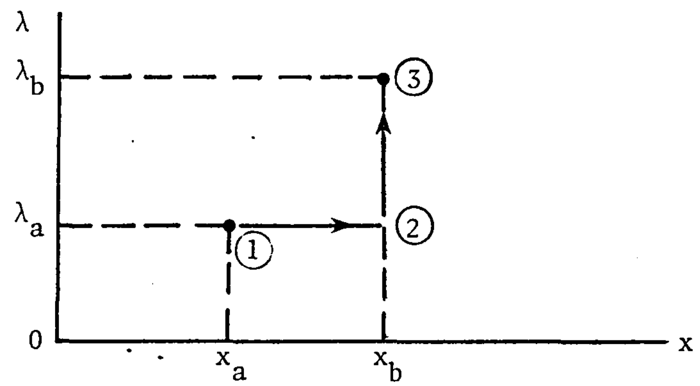

Figure 1.- Path of integration.

$$W_m(\lambda_b,x_b) - W_m(\lambda_a,x_a) = -\int_{x_a}^{x_b} f_e(\lambda_a,x)dx + \int_{\lambda_a}^{\lambda_b} i(\lambda,x_b)d\lambda \tag{5}$$

By using this path and starting with the electrical terminal values zero instead of an arbitrary value, W_m can be determined from the electrical terminal relations only. That is, when $\lambda_a = 0$ there is no force of electrical origin ($f_e(0,x) = 0$ in the integration).

Force-energy relations.- From the section above it is clear that W_m can be expressed as a function of the independent variables λ and x

$$W_m = W_m(\lambda,x) \tag{6}$$

Taking the total derivative

$$dW_m = \frac{\partial W_m}{\partial \lambda}\, d\lambda + \frac{\partial W_m}{\partial x}\, dx \tag{7}$$

and subtracting this equation from the previous equations for dW_m results in

$$\left(i - \frac{\partial W_m}{\partial \lambda}\right) d\lambda - \left(f_e + \frac{\partial W_m}{\partial x}\right) dx = 0 \tag{8}$$

Since λ and x are independent variables, $d\lambda$ and dx can have arbitrary values. This means the coefficients must be zero to satisfy the equation. Thus,

$$i = \frac{W_m(\lambda,x)}{\partial \lambda} \tag{9}$$

and

$$f_e = - \frac{\partial W_m(\lambda,x)}{\partial x} \tag{10}$$

Force coenergy relations.- In the present development it is more convenient to use i instead of λ for an independent variable. From above

$$dW_m = i\ d\lambda - f_e dx$$

$$\lambda = \lambda(i,x)$$

and

$$f_e = f_e(i,x)$$

By defining the coenergy W_m to be

$$W_m' \triangleq \lambda i - W_m \tag{11}$$

then

$$dW_m' = d(\lambda i) - i d\lambda + f_e\ dx$$

which simplifies to

$$dW_m' = \lambda di + f_e\ dx \tag{12}$$

Since $W_m' = W_m'(i,x)$

$$dW_m' = \frac{\partial W_m'}{\partial i}\ di + \frac{\partial W_m'}{\partial x}\ dx \tag{13}$$

Subtracting equations (13) from (12) results in

$$\left(\lambda - \frac{\partial W_m'}{\partial i}\right) di + \left(f_e - \frac{\partial W_m'}{\partial x}\right) dx = 0 \tag{14}$$

from which is obtained the force of electrical origin as a function of current and displacement

$$f_e = \frac{\partial W'_m(i,x)}{\partial x} \qquad (15)$$

Simplified Magnetic Bearing Element
with no Permanent Magnet

Consider the magnetic bearing element shown in figure 2.

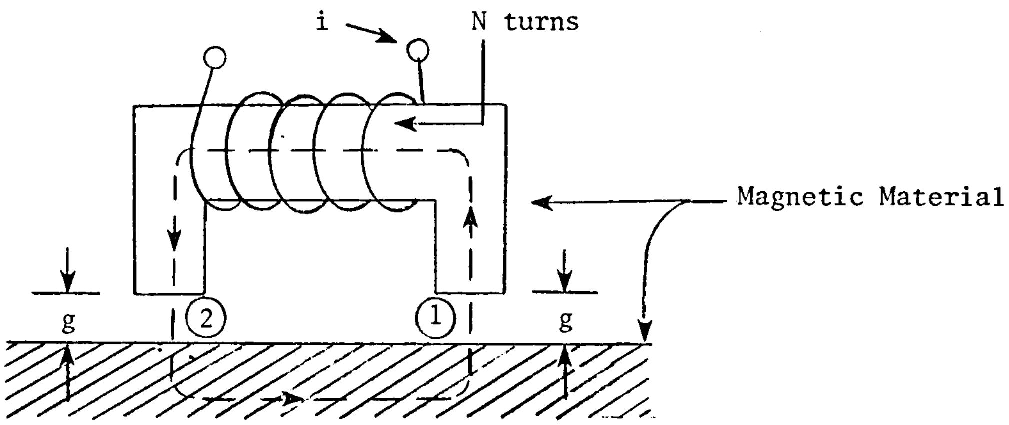

Figure 2.- Magnetic bearing element.

Assumptions: (1) Magnetic material has infinite μ

(2) Negligible fringing

(3) Negligible leakage

From equation (A7)

$$B = \mu H$$

For a finite B inside the magnetic material, with $\mu \rightarrow \infty$, $H \rightarrow 0$. This means that all the magnetic field intensity is across the air gaps. Using equation A1 and the contour shown

$$\oint_c H \cdot d\ell = H_1 g + H_2 g = \int_s J_f \cdot n da = Ni \qquad (16)$$

By symmetry it can be seen that

$$H_1 = H_2 = \frac{Ni}{2g} \qquad (17)$$

The flux density through the core is the flux through one of the gaps and is, from equation A7,

$$B = \mu_o H_1 = \mu_o H_2 = \frac{\mu_o Ni}{2g} \tag{18}$$

The flux ϕ in the core becomes

$$\phi = BA = \frac{\mu_o Ni\ A}{2g} \tag{19}$$

where A is the cross sectional area of the core. This flux links the N turn winding N times so that from the definition of λ (equation B4)

$$\lambda = N \int_s B \cdot n\ da = N\ \phi \tag{20}$$

where s is the surface enclosed by the winding. Then

$$\lambda = \frac{\mu_o AN^2 i}{2g} \tag{21}$$

From the previous definition of coenergy (equation (12))

$$dW'_m = \lambda di + f_e\ dx$$

or between the points (i_a,x_a) and (i_b,x_b)

$$W'_m = W'_m(i_b,x_b) = W'_m(i_a,x_a) = \int_{x_a}^{x_b} f_e(i_a,x)dx + \int_{i_a}^{i_b} \lambda(i,x_b)di \tag{22}$$

Integrating from $i = 0$ and substituting g for x results in

$$W'_m = \int_o^i \lambda(\bar{i},g)di$$

since

$$\int_o^g f_e(o,\bar{g})dg = 0$$

The bar represents the integration variable and (i,g) represents the end point of the integration.

W'_m then is

$$W'_m \int_o^i \left(\frac{\mu_o AN^2}{2g}\right) i\ di = \frac{1}{2}\left(\frac{\mu_o AN^2}{2g}\right) i^2 = \frac{\mu_o A(Ni)^2}{4g} \tag{23}$$

From the force-coenergy relations (equation (15))

$$f_e = \frac{\partial W_m'(i,g)}{\partial g}$$

or

$$f_e = \left(\frac{\mu_o A(Ni)^2}{4}\right)\left(-\frac{1}{g^2}\right) = -\frac{\mu_o A(Ni)^2}{4g^2} \tag{24}$$

Simplified Magnetic Bearing Element
with Permanent Magnet

Consider the magnetic bearing element with a permanent magnet in the core as shown in figure 3.

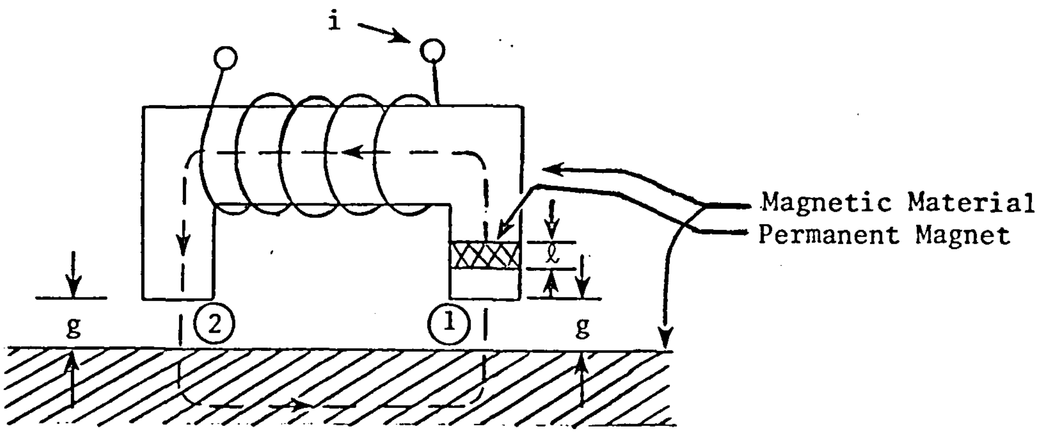

Figure 3.- Magnetic bearing element with permanent magnet.

A good approximate model of a permanent magnet is (from reference 7)

$$B_m = \mu_m H_m + B_o \tag{25}$$

Taking the line integral around the contour shown results in

$$\oint_c H \cdot d\ell = \oint_s J_f \cdot n \, da = H_1 g + H_2 g + H_m \ell = Ni \tag{26}$$

From equation (25)

$$H_m = \frac{B_m - B_o}{\mu_m} \tag{27}$$

Equation (26) becomes

$$H_1 g + H_2 g + \frac{B_m}{\mu_m}\ell = Ni + \frac{B_o}{\mu_m}\ell \qquad (28)$$

The term $\frac{B_o}{\mu_m}\ell$ is constant and can be represented by an equivalent magnetomotive force (mmf)

$$\frac{B_o}{\mu_m}\ell \stackrel{\Delta}{=} NI_o \qquad (29)$$

As before, $H_1 = H_2 = H$ and B in the air gap = B in the core. Then,

$$B = \mu_o H = B_m \qquad (30)$$

and

$$H(2g) + \frac{(\mu_o H)\ell}{\mu_m} = N(i + I_o) \qquad (31)$$

H becomes

$$H = \frac{N(i + I_o)}{2g + \frac{\mu_o}{\mu_m}\ell} \qquad (32)$$

and B becomes

$$B = \mu_o \frac{N(i + I_o)}{2g + \frac{\mu_o}{\mu_m}\ell} \qquad (33)$$

λ can then be determined as

$$\lambda = N\phi = NBA = \frac{\mu_o AN^2(i + I_o)}{2g + \frac{\mu_o}{\mu_m}\ell} \qquad (34)$$

Next, define

$$i' \stackrel{\Delta}{=} i + I_o \qquad (35)$$

Integrating from $i' = 0$ and substituting g for x results in a coenergy of

$$W_m' = \int_o^{i'} \left(\frac{\mu_o AN^2}{2g + \frac{\mu_o}{\mu_m}\ell} \right) i' \, di' = \frac{1}{2} \left(\frac{\mu_o AN^2 i'^2}{2g + \frac{\mu_o}{\mu_m}\ell} \right) \qquad (36)$$

f_e then becomes from equation (15)

$$f_e = - \frac{\mu_o AN^2 (i + I_o)^2}{\left(2g + \frac{\mu_o}{\mu_m} \ell\right)^2} \tag{37}$$

SINGLE ACTUATOR MODEL

A single AMCD axial bearing actuator, for control along a single axis, consists of a pair of magnetic bearing elements, with permanent magnets, mounted in the configuration shown in figure 4.

The bearing elements are connected in a differential configuration. That is, for a given input the amplifier driver shown in the figure produces current in a direction to aid the permanent-magnet-produced flux in one element while at the same time producing equal current in a direction to subtract from the permanent-magnet-produced flux in the other element. This results in a net force produced on the suspended mass in a direction dependent on the polarity of the input to the amplifier driver. If the force produced by the upper element is defined as F_U and that produced by the lower element as F_L and up is taken as the positive direction, the net force produced by an actuator as a function of current and gap becomes

$$F = F_U - F_L = \mu_o AN^2 \left(\frac{[I_o + i]^2}{\left[2g_U + 2 \frac{\mu_o}{\mu_m} \ell\right]^2} - \frac{[I_o - i]^2}{\left[2g_L + 2 \frac{\mu_o}{\mu_m} \ell\right]^2} \right) \tag{38}$$

The multiplication of $\frac{\mu_o}{\mu_m} \ell$ by 2 results from the fact that there are two permanent magnet wafers in each AMCD magnetic bearing element (reference 5). By making the following definitions, equation (36) can be written in a simpler form:

$$\left.\begin{aligned} \mu_o AN^2 &\triangleq K_1 \\ \frac{\mu_o}{\mu_m} \ell &\triangleq K_2 \\ g_U &\triangleq x_o - x \\ g_L &\triangleq x_o + x \end{aligned}\right\} \tag{39}$$

where x_o is the bearing gap with the rim centered and x is the displacement of the rim with respect to x_o (up is positive displacement).

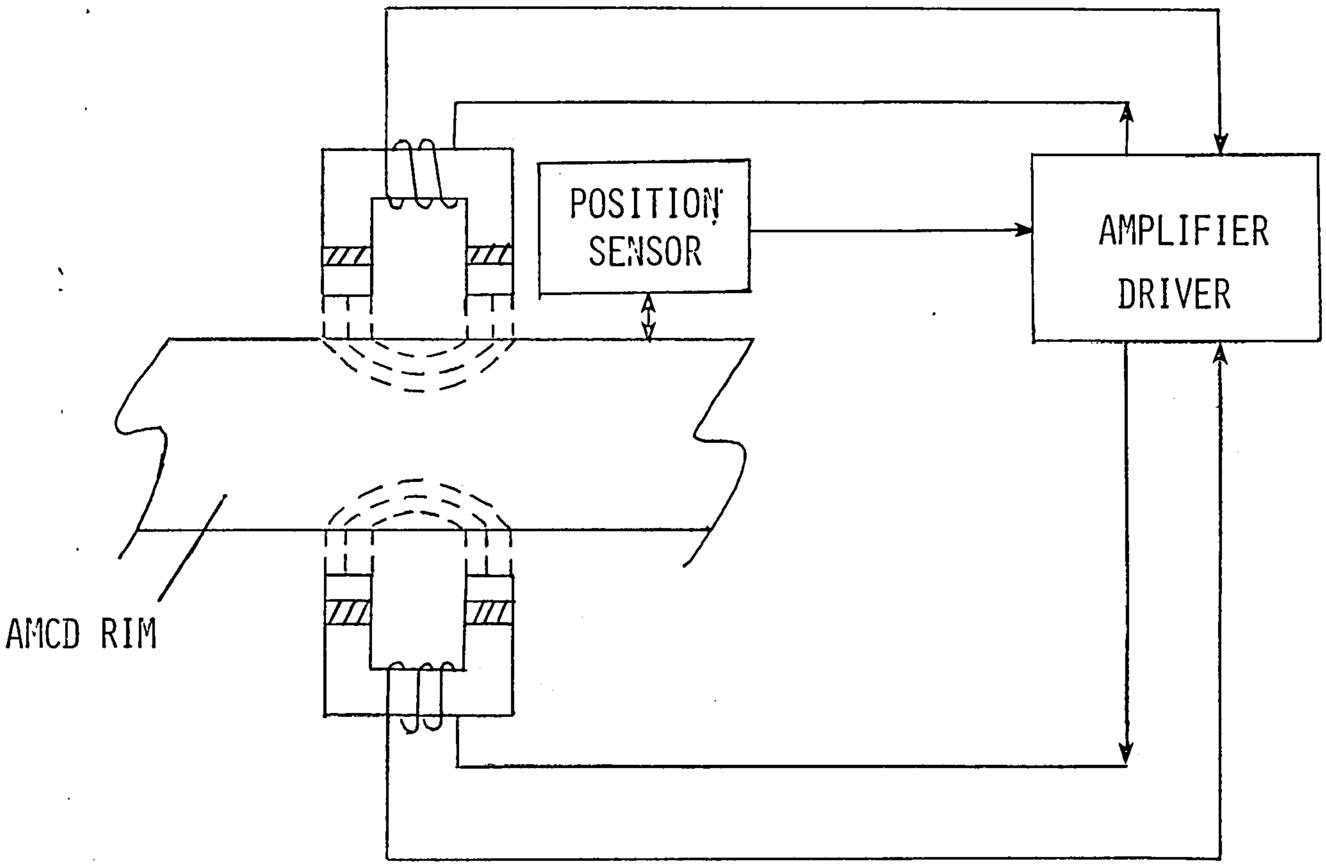

Figure 4.- Single AMCD axial bearing actuator

Equation (38) then becomes

$$F = \frac{K_1}{4}\left(\frac{[I_o + i]^2}{[x_o - x + K_2]^2} - \frac{[I_o - i]^2}{[x_o + x + K_2]^2}\right) \tag{40}$$

Finally, define

$$\bar{x}_o \stackrel{\Delta}{=} x_o + K_2 \tag{41}$$

The equation for force then becomes

$$F = \frac{K_1}{4}\left(\frac{[I_o + i]^2}{[\bar{x}_o - x]^2} - \frac{[I_o - i]^2}{[\bar{x}_o + x]^2}\right) \tag{42}$$

This equation can be linearized for small deviations about a given operating point by using the combination of linear gains

$$F = K_B i + K_m x \tag{43}$$

where $K_B \stackrel{\Delta}{=} \frac{\partial F}{\partial i}$ and $K_m \stackrel{\Delta}{=} \frac{\partial F}{\partial x}$ and are evaluated at the operating point (reference 8). Using equation (42) these gains become

$$K_B = K_1\left(\frac{I_o x^2 + 2\bar{x}_o xi + I_o \bar{x}_o{}^2}{\bar{x}_o{}^2 - x^2}\right) \tag{44}$$

and

$$K_m = \frac{K_1}{2}\left(\frac{[I_o + i]^2}{[\bar{x}_o - x]^3} + \frac{[I_o - i]^2}{[\bar{x}_o + x]^3}\right) \tag{45}$$

In the case of the AMCD laboratory model, the parameters I_o and K_1 can be obtained from hardware data. At an operating point of .635 mm (.025 inches) above center, K_B is 13.79 N/amp (3.1 lb/amp), and K_m at $i = 0$ is 59.54 N/mm (340 lb/inch) (reference 5). $\bar{x}_o$ is the gap with the rim centered, 2.54 mm (.10 inch), plus the thickness of one of the permanent magnet wafers, 1.02 mm (.04 inches) (reference 5), since $\frac{\mu_o}{\mu_m} \approx 1$. This leads to three equations ((42), (44), and (45)) and three unknowns (I_o, K_1, and i at the nominal operating point). F in equation (42) is one-third of the rim weight (16.5 lb). Solution of the equations yields I_o = 14.97 amp, K_1 = 9.9 N-mm^2/amp^2 (3.45 $(10)^{-3}$ lb-in^2/amp^2), and i at the operating point = 2.99 amp. Solving equation (45) using i at the operating point yields K_m = 73.67 N/mm (420.7 lb/in). Equation (42) then becomes

$$F = 2.475\left(\frac{[14.97 + i]^2}{[\ 3.56 - x]^2} - \frac{[14.97 - i]^2}{[\ 3.56 + x]^2}\right) \tag{46}$$

and (42) linearized around an operating point .635 mm (.025 in) above the gap center becomes

$$F = 13.79\ i + 73.67\ x \tag{47}$$

With a finite position gain, the equilibrium position of the rim will be below the sensor zero. A block diagram representation of a single bearing control loop is shown in figure 5.

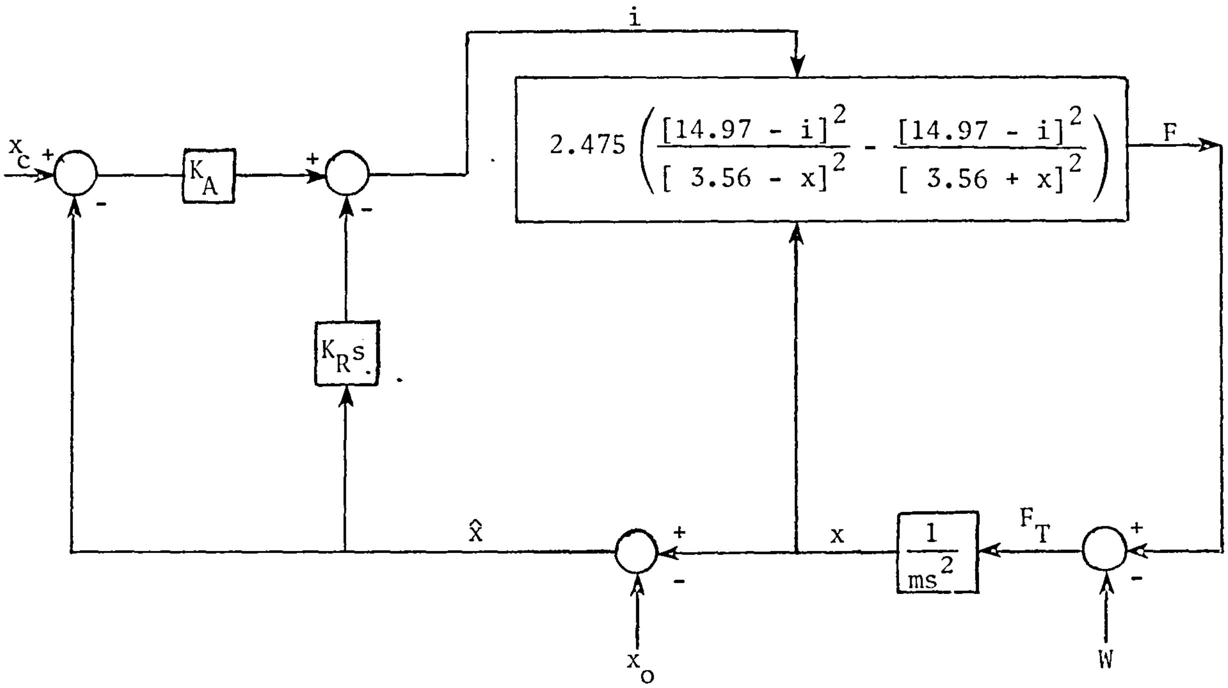

Figure 5.- Single bearing control loop.

At equilibrium with the position command, x_c, set to zero, the total force, F_T, from the figure becomes

$$F_T = 2.475\left(\frac{[14.97 + i]^2}{[\ 3.56 - x]^2} - \frac{[14.97 - i]^2}{[\ 3.56 + x]^2}\right) - W = 0 \tag{48}$$

where W represents one-third of the rim weight. The current becomes

$$i = -K_A\ \hat{x} = K_A(x_o - x) \tag{49}$$

Using the values of x_o and W from above and a value of 19.57 amp/mm (497.1 amp/in.) for K_A (reference 5), equations (48) and (49) can be solved simultaneously to yield an equilibrium position of $x = .427$ mm (.0168 in.)

and an equilibrium current of i = 4.08 amp. Substituting these values into equations (44) and (45) yields K_B = 13.03 N/amp (2.93 lb/amp) and K_m = 67.88 N/m (387.6 lb/in). Equation (42) linearized around the equilibrium point becomes

$$F = 13.03\ i + 67.88\ x \tag{50}$$

Concluding Remarks

This paper has developed a nonlinear analytical model of an annular momentum control device (AMCD) laboratory test model magnetic bearing actuator with permanent magnet flux-biasing. The actuator is treated as a lumped-parameter electromechanical system in the development. The model can be used in computer simulations to investigate the effects of large AMCD rim motions in the magnetic bearing actuator gaps.

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APPENDIX A

Magnetic Field Equations

This appendix presents the magnetic field equations used in the development of the analytical model of the AMCD magnetic bearing actuator presented in the main text of this report. For a development of these equations, see reference 7, Appendix B.

The magnetic field equations used are:

$$\oint_c H \cdot d\ell = \int_s J_f \cdot nda \tag{A1}$$

$$\oint_s B \cdot nda = 0 \tag{A2}$$

$$\oint_s J_f \cdot nda = 0 \tag{A3}$$

$$\oint_c E' \cdot d\ell = -\frac{d}{dt} \int_s B \cdot nda \tag{A4}$$

$$B = \mu_o (H + M) \tag{A5}$$

where $\oint_c$ is the line integral around a closed contour, $\int_s$ is the surface integral over a surface enclosed by a contour, $\oint_s$ is the surface integral over a surface enclosing a volume, n is a normal vector, H is magnetic field intensity, B is magnetic flux density, J_f is current density, E' is electric field intensity measured with respect to a contour that may be moving, μ_o is the permeability of free space, and M is the magnetization density which accounts for the effects of magnetizable materials. M is usually defined as

$$M = X_m H$$

where X_m is magnetic susceptibility. If the permeability of a material is defined as

$$\mu = \mu_o (1 + X_m) \tag{A6}$$

then equation (A5) can be written as

$$B = \mu H \tag{A7}$$

Appendix B

Flux Linkage

In this appendix the concept of flux linkage is discussed. For a more detailed discussion, see reference 7.

Consider a perfect conductor with terminals a and b as shown in figure B1 where the contour between a and b outside the conductor encloses no changing magnetic flux.

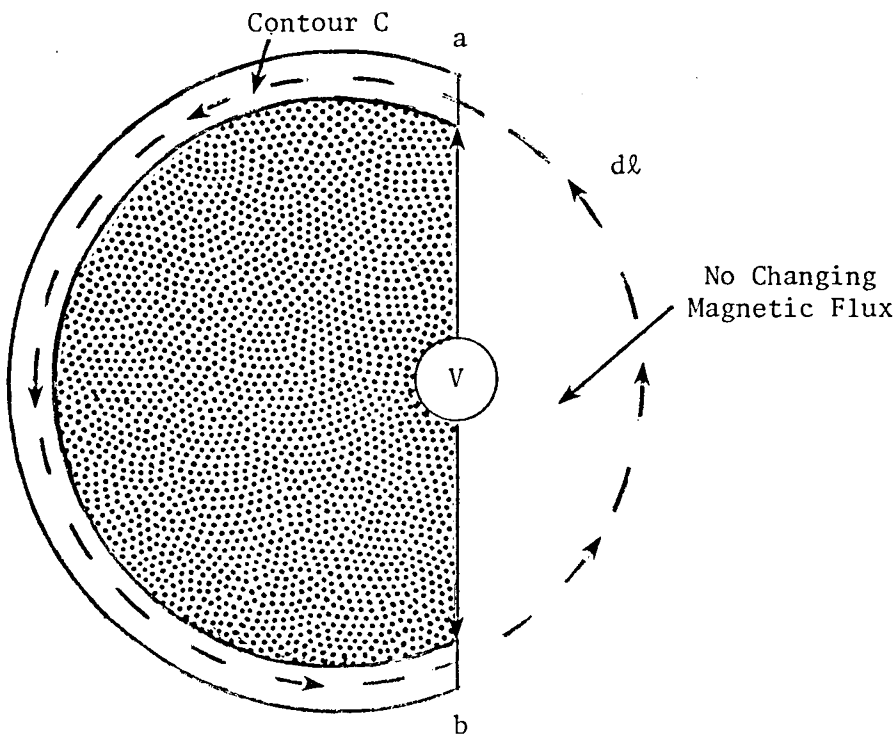

Figure B1.- Perfect conductor with terminal voltage v.

The terminal voltage v can be written as

$$v = - \int_b^a E \cdot d\ell \tag{B1}$$

where the line integral is taken from b to a outside the conductor. Since by definition a perfect conductor can support no electric field

$$\oint_c E \cdot d\ell = \int_b^a E \cdot d\ell = - v \tag{B2}$$

From equation (A4) in Appendix A

$$v = \frac{d}{dt} \int_s B \cdot nda \tag{B3}$$

Define flux linkage λ of the conductor as

$$\lambda = \int_s B \cdot nda \tag{B4}$$

v then becomes

$$v = \frac{d\lambda}{dt} \tag{B5}$$

From equations (A1) through (A4) in Appendix A, it can be seen that flux density B will be a function of terminal current (equation (A3) is used to relate terminal current to current density in the system and then (A1), (A2), and (A5) used to solve for B), material properties (equation (A5)), and system geometry. Therefore, λ is also a function of terminal current, material properties, and system geometry. If the assumption is made that geometry is fixed, except for one movable part whose position can be described instantaneously by a displacement x with respect to a fixed reference, and that M is a function of field quantities alone then

$$\lambda = \lambda(i, x) \tag{B6}$$

and

$$v = \frac{d\lambda}{dt} = \frac{\partial\lambda}{\partial i}\frac{di}{dt} + \frac{\partial\lambda}{\partial x}\frac{dx}{dt} \tag{B7}$$

where terminal voltage is shown to be a function of rate of change of current in the circuit and relative motion of the circuit.

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15. Supplementary Notes

16. Abstract

An analytical model of an Annular Momentum Control Device (AMCD) laboratory test model magnetic bearing actuator with permanent magnet flux-biasing is presented. An AMCD consists of a spinning annular rim which is suspended by noncontacting magnetic bearings and driven by a noncontacting linear electromagnetic spin motor. The actuator is treated as a lumped-parameter electromechanical system in the development of the model.

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